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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

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Additional inventors are being named on the second *separately numbered sheets attached hereto*

TITLE OF THE INVENTION (500 characters max)

Resonator Cavity Configuration and Method

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Respectfully submitted,

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Date December 18, 2003

REGISTRATION NO. 47,421
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PROVISIONAL APPLICATION COVER SHEET
Additional Page

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Docket Number 25890

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Number 2 of 2

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MAIL STOP PROVISIONAL PATENT APPLICATION
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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of:

Inventor (s): Amiel ISHAAYA et al.

Serial Number: NOT YET ASSIGNED

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Title: **RESONATOR CAVITY CONFIGURATION AND METHOD**

TRANSMITTAL LETTER

Commissioner for Patents
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Submitted herewith for filing in the U.S. Patent and Trademark Office are the following **PROVISIONAL APPLICATION:**

1) Provisional Application Cover Sheet
2) 49 page Provisional Application consisting of:
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   10 pages 57 claims
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RESONATOR CAVITY CONFIGURATION AND METHOD

FIELD OF THE INVENTION

This invention relates to a resonator cavity configuration and a method of laser beam generation.

LIST OF REFERENCES

The following references are considered to be pertinent for the purpose of understanding the background of the present invention:

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BACKGROUND OF THE INVENTION

High-power lasers are typically characterized by inferior beam quality, stability, and heat dissipation, as compared to that of lower power lasers. Combining several low-power lasers by incoherently adding the field distributions of several laser output beams results in that the combined beam-quality factor (M^2), which is the sum of the individual quality factors, is relatively poor with low optical brightness. When the field distributions are coherently added, with the proper phase relations, the combined beam quality factor can be as good as that of one low-power laser, while the combined power is greater by a factor equal to the number of the lasers.

When coherently combining two or more laser output fields, two major difficulties are encountered. The first results from the need for proper coupling between the individual laser fields, so as to enable relative phase locking between them. Such coupling typically introduces excessive losses to each laser field, and

requires very accurate relative alignment. The second (and somewhat related) difficulty results from the need for accurately controlling the relative phase between the different laser fields, so as to ensure constructive interference between them. This requires that the distances between the participating optical components must be very accurately controlled, causing the output power to be extremely sensitive to thermal drifts and acoustic vibrations.

Attempts have been made to obtain high power concomitantly with good beam quality based on intra-cavity phase locking and coherent addition of lasers [1-7]. Several techniques dealing with intra-cavity coherent addition of single transverse mode (TEM_{00}) laser beams in fiber lasers have been developed [8-11]. According to these techniques, the phase locking and coherent addition is accomplished by the use of fiber couplers. Single transverse mode fiber couplers (2x2 for example) have been used recently to obtain intra-cavity coherent addition of single transverse mode (TEM_{00}) laser beams in a fiber laser configuration [8-11]. Here, one of the output terminals of the 2x2 standard single mode fiber coupler was angle spliced so that no reflection from that terminal is present. The resulting coupler's operation when placed in a resonator is similar to that of a 50% beam splitter. This approach, however, is applicable only in fiber laser systems, and designed only for single TEM_{00} beams.

U.S. Patent No. 3,414,840 discloses a technique of synchronization of power sources. Here, two laser oscillators are used, each including a first mirror and a laser medium and each sharing in common a second mirror, and means for extracting wave energy from the oscillators. The first mirrors and the common second mirror form a pair of resonant cavities. A 3db hybrid junction, having two pairs of conjugate ports located within a common region of the cavities, is used for coupling wave energy among the mirrors and out of the cavities. The laser medium for each oscillator is located between one of the first mirrors and one port of one of the pairs of conjugate ports. This arrangement utilizes discrete beam splitters within the resonator in order to coherently add two or more laser channels, operating in the TEM_{00} transverse mode, and obtain a single transverse and longitudinal mode (single frequency) output beam.

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Techniques have also been developed for external coherent combining of two lobes of a transverse high order mode distribution emerging from a laser [12-13].

SUMMARY OF THE INVENTION

There is a need in the art to obtain high-power laser characterized by improved beam quality, stability, and heat dissipation.

The present invention solves the above problems by providing a novel approach for intra-cavity coherent addition of two or more laser beams that enables stable operation. The present invention takes advantage of synchronizing and coherently adding two or more laser oscillators (with one or more gain media), to produce a higher power output, and utilizes various new intra-cavity couplers and laser resonator configurations in order to add two or more TEM_{00} mode beams, two or more single high-order-transverse-mode beams, and two or more transverse multimode beams. Additionally, the technique of the present invention enables one laser beam with the lowest transverse modal content to impose its low transverse modal content on the other participating laser beam(s), so that all beams can be phase locked, as well as phase locked and added coherently within the laser cavity. The present invention also provides for unique couplers incorporated in a laser cavity for coupling between beams propagating through the laser cavity. Such coupler could contain several optical elements on a single glass substrate, and is thus extremely compact and stable against vibrations and thermal drifts.

Thus, according to one broad aspect of the present invention, there is provided a resonator cavity comprising at least one gain medium and end reflectors which define together longitudinal modes of light propagating through the cavity, the cavity further comprising

(a) a beam coupler assembly operable to split light impinging thereon into a predetermined number of spatially separated light channels, and to cause at least partial coherent combining of the light channels, having common longitudinal and transverse modes, in a double pass through the beam

coupler assembly, to thereby produce at least one output combined light channel;

(b) an aperture arrangement configured to select, from at least one of said spatially separated light channels, a predetermined transverse mode content that is desired at the cavity output.

The beam coupling assembly may be configured to provide coherent combining of the light channels to produce the single output combined channel. Alternatively, the beam coupler assembly may be configured to provide partial coherent combining of the channels, where each channel gives away or receives some coupling power to one or more other channels, and thus produce a multiplicity of spatially separated output light channels, which are phase locked.

The desired lowest transverse mode content at the output is produced by inserting the appropriately designed aperture arrangement into at least one channel. Alternatively, a multiple-aperture arrangement can be exploited, each for a separate channel.

According to one embodiment of the invention, in which two or more laser beams are phase locked and coherently added, the beam coupler assembly is an interferometric coupler assembly. In the simplest implementation of such an interferometric coupler, the coupler, formed with discrete and separate elements, is a beam splitter/combiner of predetermined transmission/reflection, for example as that disclosed in the above-indicated U.S. Patent 3,414,840. Considering N gain media in the resonance cavity producing N light channels, respectively, the beam coupler assembly includes $(N-1)$ simple beam splitter/combiners.

In another possible implementation of the interferometric coupler, the coupler is a planar interferometric two-beam coupler. The coupler is formed of a high precision plane parallel plate with specially designed coatings. According to yet another possible implementation, the coupler is a planar interferometric N-beam coupler. This coupler is somewhat more complex than the simple two-beam coupler, and is used for intra-cavity phase locking and subsequent coherent addition of more than two laser beams.

The planar interferometric coupler element for coherent addition is preferably a plane parallel plate with its front or rear facet or each of the front and rear facets having a predetermined pattern formed by regions of different transmission/reflectivities. The plane parallel plate has a predetermined thickness d and is oriented with respect to a light propagation axis at a predetermined angle defining a certain angle α of light incidence onto the plate so as to ensure said splitting and said at least partial coherent combining of the light channels in the double pass through the plate.

For the incident angle α, the thickness d of the plate is determined as:

$$d = x_0 / \{2 \cos\alpha \, tg[\arcsin(\sin\alpha / n)]\}$$

wherein x_0 is a distance between propagation axes of the light channels, and n is a refractive index of a material of the plate, thereby providing for matching the distance between the light channels so as to enable an optimal overlap between the light channels and their collinear propagation after exiting the beam coupler assembly.

The regions of the different reflectivities on the front facet include a substantially transmitting region (e.g., with an anti-reflecting coating), so as to transmit most, if not all, of the incident light, and include at least one region of a predetermined beam splitting property. The regions of the different reflectivities on the rear facet include a relatively large highly reflective region, and may include a substantially transmitting region (e.g., an anti-reflecting coating). When operation of the beam coupler assembly in the reflection mode is desired, the rear facet may be entirely highly reflective. Alternatively, the reflection mode operation may be achieved by placing the output end reflector in the optical path of a light portion reflected from the beam splitting region on the front facet. Generally, the need for anti-reflecting coatings can be eliminated by orienting the beam coupler at a Brewster angle with respect to the cavity axis, and by operating with a specific linear polarization of light.

The dimensions of the regions of different reflectivities of the front and rear facets and the orientation of the plane parallel plate is such that: the substantially transmitting region of the front facet is aligned with the highly reflective region of

the rear facet thereby allowing light passage through the plate to the highly reflective region where it is reflected towards the beam splitting region in the front surface and then the light is reflected towards the highly reflective region, and so on; and optionally, especially when operation in the transmission mode is required, one beam splitting region of the front facet is aligned with the substantially transmitting region of the rear facet, so that the light propagation through these regions defines a light output of the beam coupler.

The front facet of the plane parallel plate may comprise the single beam splitting region, thereby producing two light channels. Generally, the front facet has the substantially transmitting region (e.g., anti-reflective coating) and *(N-1)* beam splitting regions for *N* light channels, respectively. Each *i*-th beam splitting region, i=2,...N, has a reflectivity of (1-1/i) or a transmittance of 1/*i*, such that the first light channel is substantially not affected by the front facet and the other *(N-1)* light channels are differently affected by the *(N-1)* beam splitting regions, respectively.

The planar interferometric coupler assembly may comprise the single plane parallel plate with the patterned front and rear facets. Alternatively, the interferometric coupler assembly may include a pair of first interferometric coupler elements (e.g., the above-described patterned plane parallel plates) associated with a pair of the gain media, respectively, and operating to produce two combined light components, respectively; and a second interferometric coupler element (e.g., the patterned plane parallel plate) for coupling these two combined light components, to produce the single output coherently combined channel.

The interferometric coupler assembly may be configured as a phase locking coupler assembly. Similarly, this is preferably a plane parallel plate with patterned front and rear facets, which has a predetermined thickness and predetermined orientation with respect to the cavity axis. The regions of the different reflectivities on the front facet include a substantially transmitting region (e.g., with an anti-reflecting coating) and at least one region of a predetermined partially light transmitting property, and the regions of the different reflectivities on the rear facet include at least one region of a predetermined partially light transmitting property and a substantially transmitting (anti-reflecting) region. The dimensions of these

regions and the orientation of the plane parallel plate are such that one partially transmitting region of the front facet is aligned with the substantially anti-reflecting region of the rear facet. The substantially anti-reflecting region of the front facet is aligned with the partially transmitting region of the rear facet thereby allowing light passage through the plate to the partially transmitting region on the rear facet. Light is reflected from the partially transmitting region of the rear facet towards the partially transmitting region of the front facet; and then the light is reflected back towards the partially transmitting region on the rear facet, and so on.

According to another embodiment of the invention, the beam coupler assembly is configured for polarization coupling of the light channels. Polarization couplers are based on exploiting the polarization state of the beams and the effect of conventional polarizers on this state. The polarization coupler assembly includes two polarizers accommodated in a spaced-apart relationship along the cavity axis; and an optical element configured as a $\lambda/2$ retardation plate or 45° polarization rotator accommodated between the two polarizers.

The aperture arrangement may be configured to define a single aperture associated with one of the light channels, or multiple apertures associated with the light channels, respectively. The aperture has a diameter capable of selecting the desired lowest transverse mode content from the respective light channel, which may be Gaussian mode distribution, the desired multiple-transverse-mode distribution, or single high-order transverse-mode distribution in which case an appropriate phase element is used.

According to another aspect of the present invention, there is provided a beam coupler element for use in a resonator cavity for affecting the light propagation through the resonator cavity to provide an output light channel in the form of coherent addition of at least two light channels having at least one common longitudinal mode, the beam coupler assembly comprising:

- a plane parallel plate with its front and rear facets being patterned to have regions of predetermined transmission or reflectivities, wherein
- the front facet includes a substantially transmitting region and *(N-1)* beam splitting regions for *N* light channels, respectively, each *i*-th beam splitting

region, i=2,...N, having a reflectivity of (1-1/i) or a transmittance of $1/i$, such that the first light channel is substantially not affected by the front facet and the other *(N-1)* light channels are differently affected by the *(N-1)* beam splitting regions, respectively;

- the rear facet includes a highly reflective region; and
- dimensions of said regions of the front and rear facets and orientation of the plane parallel plate with respect to the light channels' propagation axis are such that light is reflected from the highly reflective region towards the beam splitting region and *vice versa.*

According to yet another aspect of the present invention, there is provided a beam coupler element for use in a resonator cavity for affecting the light propagation through the resonator cavity to provide at least two output light channels of desired transverse/longitudinal modes, the beam coupler assembly comprising:

- a plane parallel plate with its front and rear facets being patterned to have regions of predetermined transmission or reflectivities, wherein
- the front facet includes a substantially transmitting region and at least one predetermined beam splitting region;
- the rear facet includes a substantially transmitting region and at least one predetermined beam splitting region; and
- dimensions of said regions and orientation of the plane parallel plate with respect to the light channels' propagation axis are such that light is reflected from the beam splitting region of the rear facet towards the beam splitting region of the front facet and *vice versa.*

According to yet another aspect of the present invention, there is provided a method of controlling the light propagation through a resonator cavity, which is formed by at least one gain medium and end reflectors that define together longitudinal modes of the cavity, to produce output from the cavity of at least one desired longitudinal and transverse mode distribution, the method comprising:

- splitting light generated by the gain medium into a predetermined number of spatially separated light channels each including light of said at least one desired longitudinal mode;
- selecting in one or more of the light channels the desired transverse mode content;
- applying interferometric coupling to the light channels so as to cause at least partial coherent combining of the light channels and thereby produce at least one combined light channel of the desired longitudinal and transverse mode distribution.

According to yet another aspect of the present invention, there is provided a method of controlling the light propagation through a resonator cavity, which is formed by at least one gain medium and end reflectors that define together longitudinal modes of the cavity, to produce output from the cavity of at least one desired longitudinal and transverse mode distribution, the method comprising:

- providing a predetermined number of spatially separated light channels each including light of said at least one desired longitudinal mode;
- selecting in one or more of the light channels the desired transverse mode distribution;
- applying interferometric coupling to the light channels so as to cause at least partial coherent combining of the light channels and thereby produce at least one combined light channel of the desired longitudinal and transverse mode distribution.

In its yet another aspect, the present invention provides a method of controlling light propagation through a resonator cavity, which is formed by at least one gain medium and end reflectors that define together longitudinal modes of the cavity, to produce output from the cavity of at least one desired longitudinal and transverse mode distribution, the method comprising:

- providing a predetermined number of spatially separated light channels each including light of said at least one desired longitudinal mode;
- selecting in one or more of the light channels the desired transverse mode distribution;

- applying polarization coupling to the light channels so as to cause at least partial coherent combining of the light channels and thereby produce at least one combined light channel of the desired longitudinal and transverse mode distribution.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the invention and to see how it may be carried out in practice, preferred embodiments will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

Fig. 1 is a schematic illustration of a resonator cavity configuration according to one embodiment of the invention, configured for intra-cavity coherent addition of two Gaussian beam distributions using a single interferometric coupler;

Fig. 2 is a schematic illustration of a laser cavity configuration according to another embodiment of the invention, configured for intra-cavity pair coherent addition of four Gaussian beam distributions using interferometric couplers;

Fig. 3 is a schematic illustration of a laser cavity configuration according to yet another embodiment of the invention, configured for intra-cavity sequential coherent addition of several Gaussian beam distributions using a single interferometric coupler;

Fig. 4 more specifically illustrates a planar interferometric coupler used in the example of Fig. 3, designed to phase lock and coherently add N light channels when placed in the resonator;

Fig. 5 is a schematic illustration of a laser cavity configuration according to yet another embodiment of the invention, configured for intra-cavity coherent addition of two Gaussian beam distributions using a polarization coupler;

Fig. 6 is a schematic illustration of a laser cavity configuration according to yet another embodiment of the invention, configured for intra-cavity coherent addition of four Gaussian beam distributions using polarization couplers;

Fig. 7 is a schematic illustration of a laser cavity configuration according to yet another embodiment of the invention, configured for intra-cavity coherent

addition of two single high-order TEM_{01} transverse mode beam distributions using a single interferometric coupler;

Fig. 8 is a schematic illustration of a laser cavity configuration according to yet another embodiment of the invention, configured for intra-cavity coherent addition of two multimode transverse beam distributions using a single interferometric coupler;

Figs. 9A and 9B schematically illustrate the principles of intra-cavity coherent addition of several single (or multiple) mode beam distributions derived from separate fiber lasers using discrete beam splitters couplers, wherein **Fig. 9A** shows intra-cavity sequential addition configuration and **Fig. 9B** shows intra-cavity coherent addition of pairs configuration;

Fig. 10 schematically illustrates yet another embodiment of the invention, where one channel imposes a Gaussian mode on the other channel and coherent addition of the two beams distributions is achieved using a single interferometric coupler;

Fig. 11 schematically illustrates the embodiment of the invention, where one channel imposes a single high-order transverse mode on the other channel and coherent addition of the two high order mode distributions is achieved using a single interferometric coupler;

Fig. 12 schematically illustrates the embodiment of the invention, where one channel imposes a specific multimode content on the other channels and sequential coherent addition of the four beams is achieved using a single interferometric coupler;

Fig. 13 schematically illustrates the embodiment of the invention, where the common channel imposes Gaussian mode content on the two channels and coherent addition of the two beams is achieved using a single interferometric coupler;

Figs. 14 to 16 illustrate yet another embodiment of the invention utilizing phase locking of laser beams, wherein **Fig. 14** shows intra-cavity phase locking of two Gaussian beam distributions using a single interferometric coupler, **Fig. 15** shows the calculation results for the feedback after a double pass through the coupler of Fig. 14 for three cases, corresponding to, respectively, incoherent

summation of laser beams, and positive and negative coherent summation of the beams; and **Fig. 16** shows intra-cavity phase locking of four Gaussian beam distributions using a single interferometric weak coupler.

Figs. 17A and 17B schematically illustrate the principles of the present invention aimed at improving the beam quality of multimode resonators, wherein **Fig. 17A** shows the general configuration of the multimode laser resonator and **Fig. 17B** shows a laser resonator of the present invention with an array of 2x2 Gaussian beam distributions; and

Fig. 18 schematically illustrates a possible pulsed Nd:YAG laser experimental setup used for intra-cavity coherent addition of two Gaussian beam distributions.

DETAILED DESCRIPTION OF THE INVENTION

The present invention provides for a novel method and cavity configuration enabling intra-cavity phase locking, or intra-cavity phase locking and coherent addition, of two or more laser beams. Various examples of the laser cavity configurations of the present invention are described below. The configurations are shown in the figures schematically, and it should be understood that these configurations could be realized with basically all types of stable resonators (various mirror curvatures or other intracavity optical elements), with various types of gain mediums (gas, solid-state, diode, fiber, etc.), with various types of operation methods (CW, pulsed free running, Q-switched pulsed, etc.), etc.

Referring to **Fig. 1**, there is schematically illustrated an example of a resonator cavity, generally at **10**, configured for intra-cavity phase locking and coherent addition of two light channels. The resonator cavity **10** typically includes a back mirror **12** and an output coupler **14** (constituting end reflectors, respectively), and a gain medium **16** (laser rod), which together define the longitudinal modes (frequencies) of the cavity **10**. The back mirror **12** is preferably flat, while the output coupler **14** may be either flat or concave for stable laser operation. The resonator cavity **10** further includes an aperture arrangement **18**, which in the

present example is accommodated between mirror **12** and gain medium **16**; and a beam coupler assembly **20** accommodated adjacent to the gain medium **16**.

Generally, the beam coupler assembly of the present invention is configured to split the laser light into a predetermined number of spatially separated light channels and to cause either a partial combining of the light channels, or coherent addition of the light channels with common longitudinal modes (frequencies) and common transverse modes, to thereby produce one or more output combined light channels. The beam coupler assembly is configured to involve a loss mechanism whereby the beams do not suffer any loss in case of a specific relative phase between the beams, and suffer severe losses otherwise. The aperture arrangement is configured to select in at least one light channel a predetermined transverse mode content that is desired at the cavity output.

In the present example of **Fig. 1**, the cavity **10** is configured for coherently adding two Gaussian TEM_{00} beam distributions. Consequently the aperture arrangement **18** includes a double-aperture with diameters suitable for fundamental TEM_{00} operation in each of the two channels. The beam coupler assembly **20** is configured for interferometric coupling and includes a single coupling element in the form of a planar interferometric two-beam coupler.

It should be noted that instead of using the single gain medium (laser rod) with two channels, two separate laser rods can be used. In this case, a back mirror arrangement could include two back mirrors associated with two laser rods, respectively.

The beam coupler **20** is formed of a high precision plane parallel plate **21**, the front and rear facets of the plate having specially designed patterns, namely, regions of different transmission/reflectivity. The front facet has a light transmitting region **21A** (e.g., coated with an anti-reflection layer) and a beam splitting region **21A'**, and the rear facet has a light transmitting region **21B** (e.g., coated with an anti-reflection layer) and a highly reflective region **21B'**.

It should be noted that in this example, as well as in all other examples, by orienting the beam coupler at a Brewster angle with respect to the cavity axis and operating with a specific linear polarization of light eliminates the need for anti-

reflecting coatings. It should also be noted that although the examples of the invention herein described show the transmission mode of the beam coupler assembly, it should be understood that the principles of the present invention can be utilized when a reflection mode operation is desired. This can be implemented by placing the output coupler **14** so as to be in the optical path of a light portion reflected from the beam splitting region on the front facet, and optionally also making the entire rear facet highly reflective and adding another substantially transmitting region on the front facet.

The plate **21** has a predetermined thickness d and is oriented with respect to the cavity axis **OA** (i.e., to the laser beams) at a predetermined angle defining a certain angle α of light incidence onto the plate so as to match the distance between two beams **A** and **B** thus providing for the two beams optimal overlapping and collinear propagation after exiting the coupler through the anti-reflective region **21B** (i.e., to ensure the splitting and coherent addition of two light channels). For an incident angle α, thickness d is determined by the simple relation:

$$d = x_0 / \{2 \cos\alpha \, tg[\arcsin(\sin\alpha / n)]\}$$

where x_0 is the distance between the two beams **A** and **B**, and n is the refractive index of the coupler material.

The dimensions of the pattern regions and the orientation of the plate are such that the light transmitting region **21B** and the beam splitting region **21A'** are aligned, so as to define the output of the coupler **20** for the combined channel **C**, and the light transmitting region **21A** and the highly reflective region **21B'** are aligned so as to ensure that light is reflected from the highly reflective region **21B'** towards the beam splitting region **21A'**. Thus, the beam of one channel **A** is directly incident on the beam splitting region **21A'**, while the beam of the other channel **B** is transmitted through the anti-reflective region **21A**, reflected back from the rear facet region **21B'** and is incident on the beam splitter coating **21A** so as to be collinear with the transmitted beam **A**.

In this specific example, where the channels are produced by the same gain medium **16**, input beams **A** and **B** are of substantially equal intensities. Accordingly, one half **21A** of the front facet is substantially transmitting and the other half of this

facet is coated with a 50% beam splitter layer **21A'**, while half of the rear facet is coated with the highly reflecting layer **21B'** and the other half **21B** of this facet is substantially transmitting. It should be understood that in case of different intensities of the input beams **A** and **B** (different gain levels), an appropriate transmission of the front and rear facets of the coupler **20** should be chosen.

If the input beams **A** and **B** incident on the 50% beam splitter are in phase, there would be no loss. If the two input beams have a π-phase difference, then destructive interference would occur and there would be 100% losses. If the input beams have random relative phase between them (incoherent), then each beam will suffer 50% loss at the coupler **20**, so, typically, no lasing will occur. Hence, if the beams add coherently, then the losses introduced by the coupler may be completely suppressed. Indeed, the combined laser will tend to operate so that the losses are minimum, whereby the phases of the individual beams will be automatically matched (automatic phase locking) such that coherent addition takes place. This of course can be achieved only for those longitudinal modes (frequencies) that are common in the two laser channels. Thus, care must be taken to either perfectly equalize the optical length of the two resonator channels, or alternatively, to imbalance them in such a manner so as to obtain one or more mutual longitudinal modes. To this end, additional optical elements, such as optical cubes or plates, could be inserted into the channels to obtain the appropriate optical path lengths.

The configuration of Fig. 1 can be generalized to intra-cavity coherent addition of more than two beams. This is exemplified in **Fig. 2**. The same reference numbers are used for identifying those components that are common in all the examples of the invention. **Fig. 2** shows a resonance cavity configuration **100** providing for automatically phase locking and coherently adding four Gaussian beam distributions $\mathbf{B_1}$-$\mathbf{B_4}$ to form a single Gaussian TEM_{00} output beam **C**. This addition method will be referred to as "pair addition", since the beams are added in pairs. It should be understood that the pair addition could be extended to more than two beam pairs. In this technique, all laser channels have at least one mutual longitudinal mode (frequency), which is easier to achieve with a smaller number of laser channels.

The device **100** includes a pair of back mirrors **12A** and **12B**; gain media **16A** and **16B** (laser rods) associated with the mirrors **12A** and **12B**, respectively; a pair of double-aperture arrangements **18A** and **18B** associated with laser rods **16A** and **16B**, respectively; an interferometric beam coupler assembly **120**; and an output coupler **14**. The diameter of each of the apertures is such as to select from the respective channel Gaussian beam distribution. The beam coupler assembly **120** includes two interferometric couplers **20A** and **20B** accommodated in optical paths of light passing through the laser rods **16A** and **16B**, respectively; and an additional planar two-beam interferometric coupler **20C** downstream of the couplers **20A** and **20B** (with respect to the direction of light propagation from the back mirror to the output coupler).

The front and rear facets of each of the couplers **20A** and **20B** are partially coated with, respectively, 50% transmitting coating **21A'** and highly reflective coating **21B'**. The couplers **20A** and **20B** are configured and located such that their coating-patterns (50% transmitting and highly reflective regions **21A'** and **21B**) are oriented symmetrically identical with respect to the cavity axis **OA**. The coupler **20C** is a planar interferometric two-beam coupler as that described above with reference to Fig. 1.

Coupler **20A** (when in the resonator) perform phase locking and coherent addition of channels $\mathbf{B_1}$ and $\mathbf{B_2}$, produced by gain medium **16A**, resulting in a combined beam $\mathbf{C_1}$. Coupler **20B** performs phase locking and coherent addition of channels $\mathbf{B_3}$ and $\mathbf{B_4}$, produced by gain medium **16B**, resulting in a combined beam $\mathbf{C_2}$. Coupier **20C** carries out coherent addition of beams $\mathbf{C_1}$ and $\mathbf{C_2}$, resulting in a combined output channel **C**.

Fig. 3 schematically illustrates another example of a laser cavity configuration **200** for intra-cavity sequential coherent addition of more than two Gaussian beams. The device **200** includes a back mirror **12**; a gain medium **16**; a multi-aperture arrangement **218**; a beam coupler **220** including a single planar interferometric *n*-beam coupler; and an output coupler **14**. The aperture diameters are adjusted to select the Gaussian mode.

The beam coupler **220** is somewhat more complex than the above-described two-beam coupler, and is used for intra-cavity phase locking and sequential coherent addition of more than two laser beams. The coupler **220** is made of a high precision plane parallel plate **21**, with most of its back (rear) facet being coated with a highly reflective layer **21B'**, while the front facet has 4 sub-areas for 4 light channels, respectively: the first sub-area **21A** (associated with the first channel $\mathbf{B_1}$) is substantially transmitting (zero reflectivity) and the other three sub-areas $\mathbf{21A^{(2)}}$ - $\mathbf{21A^{(4)}}$ (associated with channels $\mathbf{B_2}$-$\mathbf{B_4}$, respectively) are coated with different beam-splitter coatings having different transmittance, respectively, namely, 50%, 33.3% and 25%. Minimal loss will be obtained in this configuration if channel $\mathbf{B_1}$ is coherently added (on the 50% coating) with channel $\mathbf{B_2}$, the so-produced combined channel $\mathbf{C_1}$ coherently add with channel $\mathbf{B_3}$ (at the 33% coating), and the combined channel $\mathbf{C_2}$ coherently add with channel $\mathbf{B_4}$ (at the 25% coating) to produce a combined output channel $\mathbf{C_3}$.

Under certain conditions, the laser will tend to operate such that all channels phase lock and add up coherently, so that a Gaussian TEM_{00} beam with increased power is obtained at the output. To ensure that there is at least one common longitudinal mode (frequency), additional optical elements, such as optical cubes or plates, could be inserted into the channels to obtain the appropriate optical path lengths.

In the present example of Fig. 3, the coupler **220** is designed to phase lock and coherently add four beams. It should, however, be understood that it can be used to coherently add a larger number of beams. This is illustrated in Fig. 4, showing an intra-cavity beam coupler **1220** configured for phase locking and coherent addition of *n* beams with common longitudinal modes (frequencies) and common transverse mode (e.g., Gaussian mode). The coupler **1220** is made of a high precision plane parallel plate **21**, with most of its back (rear) facet being coated with a highly reflective layer **21B'**, and the front facet having *N* sub-areas for *N* light channels, respectively: first sub-area (associated with the first channel) being substantially transmitting **21A** (zero reflectivity) and the other *(N-1)* sub-areas being coated with different beam-splitter coatings, generally at $\mathbf{21A^{(i)}}$ (i=2,…,N)

having different reflectivities, respectively. Generally, each *i*-th beam splitting region has a reflectivity of (1-1/i) or a transmittance of $1/i$, such that the first channel is not affected by the front facet and all the other channels are differently affected by the (N-1) regions with transmittance 0.5, 0.33, ... , 1/N, respectively.

For each orientation or thickness of the beam coupler, there exists a specific relative phase between two consecutive beams which will cause all the beams $\mathbf{B}_1$-$\mathbf{B}_n$ to coherently add at the output, producing an increase in output power by a factor of n. If the relative phase between the input beams has a different value or is random, then the beams would suffer losses. In this coupler, the first beam $\mathbf{B}_1$ is added with the second $\mathbf{B}_2$, then both are added with the third $\mathbf{B}_3$, and so on. Hence, each beam is sequentially added to the previously combined beams.

It should be noted that in all the configurations described above, if the gain in each channel is different, such that the power of the different channels is unequal, then appropriate beam splitter transmission should be used.

Reference is now made to **Fig. 5** illustrating a resonator cavity configuration **300** according to another embodiment of the invention. The cavity **300** is configured for intra-cavity coherent addition of two Gaussian beam distributions using polarization coupling. The device **300** includes back mirrors **12A** and **12B**, gain media **16A** and **16B**, single-aperture arrangements **318A** and **318B**, a polarization coupler arrangement **320**; and an output coupler **14**. The configuration defines channels $\mathbf{C}_1$ and $\mathbf{C}_2$.

Polarization couplers are based on exploiting the polarization state of beams and the effect of conventional polarizers on this state. The coupler **320** includes two polarizers **322A** and **322B** and an optical element **323** configured as a $\lambda/2$ retardation plate or 45° polarization rotator.

Minimal losses at polarizer **322A** will occur if channel $\mathbf{C}_1$ has pure *p*-polarization and channel $\mathbf{C}_2$ has pure *s*-polarization. If the $\lambda/2$ retardation plate **323** (or 45° polarization rotator) is aligned so as to change the polarization plane by 45°, then minimal losses at polarizer **322B** will be achieved only if the two beams $\mathbf{C}_1$ and $\mathbf{C}_2$ have a specific relative phase when reaching polarizer **322B** (0 or π phase, depending on whether the polarization was changed by ±45°). If, for example, the

beams C_1 and C_2 have the correct polarization states but the relative phase between the beams is random, then each beam will suffer 50% loss when passing through the coupler. Hence, this coupler **320** will coherently add only two beams with specific polarizations and relative phase at the input. It is thus evident that with the polarization coupler **320**, minimal losses are obtained if channel C_1 is *p*-polarized and channel C_2 is *s*-polarized, and if both are in phase. In this case, the laser **300** will tend to arrange the polarization state and the phases such that minimal loss state is obtained.

It should be noted that instead of using the $\lambda/2$ retardation plate or the 45° polarization rotator, it is possible to align the second polarizer **322B** at a 45°, and achieve the same performance. It is also possible to reduce/control the losses to the undesired phase states by using a series of Brewster plates instead of the polarizer **322B**.

The above concept can be generalized to pair addition of more than two Gaussians. This is exemplified in **Fig. 6** showing a resonance cavity **400** configured for intra-cavity coherent addition of four Gaussian beams. The cavity **400** is formed by two arrangements **402** and **404** each including all the elements of the above-described device **300** except for output coupler (namely, includes back mirrors, apertures, gain media, and polarization coupler); an additional common polarization coupler **420'**; a $\lambda/2$ or 90° rotator **423'** in the optical path of light output from one of the arrangements **402** and **704** - arrangement **404** in the present example; and an output coupler **14**. The polarization coupler **420'** is configured generally similar to coupler **420**, namely includes two polarizers **422A** and **422B** and a $\lambda/2$ retardation plate or 45° polarization rotator **423** therebetween.

The present invention also provides for obtaining increased output power from a resonator cavity, by intra-cavity phase locking and coherent addition of single high-order mode beams. This can be implemented by introducing an appropriately designed phase element (or any other suitable mechanism, such as absorptive wires, phase strips, etc.) into the resonator cavity of each of the above-described configurations to select the same single high order mode in each of the

channels. The use of phase elements in order to select high-order transverse modes is described for example in [14].

Fig. 7 shows a laser cavity **500** configured for intra-cavity coherent addition of two single high-order TEM_{01} transverse mode beam distributions using a single interferometric coupler. The device **500** includes a back mirror **12**; a double aperture arrangement **518**; a phase element **505**; a gain medium **16**; a beam coupler assembly **20**; and an output coupler **14**. Here, the aperture's diameter is adjusted to select a high-order mode distribution. The beam coupler **20** is a planar two-beam interferometric coupler as described above. As shown in the figure, the phase element **805** creates a π-phase step for each of two channels $\mathbf{C_1}$ and $\mathbf{C_2}$ and thus selects the TEM_{01} mode distribution in each channel. If light components from the two channels are added incoherently, each light component will suffer 50% losses. With coherent addition, the laser will "chose" to operate such that the two high-order mode beams are phase locked and coherently add at the beam coupler **20**. The use of this concept of intra-cavity phase locking and coherent addition of single high order mode beams provides for obtaining higher output powers than with Gaussian beam combining, and provides for the potential beam quality of the high order mode beam at the output to be as good as that of a Gaussian.

The technique of the present invention also provides for intra-cavity coherent addition of transverse multimode beams. This is exemplified in **Fig. 8**, showing a resonance cavity configuration **600**, which is generally similar to that of Fig. 1 for coherent addition of two Gaussian beams, but distinguishes therefrom in that double apertures arrangement **618** has diameters that enable transverse multimode operation in both channels. Minimal loss to both beams at the coupler **20** will be achieved if each of the transverse mode distributions is phase locked and coherently adds with the corresponding mode distribution in the other channel. Specifically, each individual mode distribution of the overall multimode distribution in one channel will be phase locked and coherently add up to those of the multimode distribution in the other channel: the TEM_{00} mode in both channels will be phase locked and will coherently add up, the TEM_{01} mode in both channels will be phase locked and will coherently add up, and so on. In this case, the

resonator cavity **600** will "chose" to operate in this minimal loss state, so that the output beam is a multimode beam (with the same M^2 as that of the single channel beam) but with twice the power. This can be looked upon as coherent addition of multimode beams, where each transverse mode is coherently added, but there is random phase between the various transverse modes.

It should be noted that, generally, each of the above-described examples of the resonator cavity of the present invention can be used to intra-cavity phase lock and coherently add two or more transverse multimode beams, provided suitable apertures are used. Moreover, channels with the same multimode distribution content but different powers can be added coherently, using suitable couplers (with appropriate beam splitting region(s)).

The inventors have found that the resonator cavity may utilize a simple beam splitter coupler for intra-cavity coherent addition of multimode beams (using suitable apertures) or for intra-cavity coherent addition of single high-order mode beams (using, in addition, suitable phase elements as described above). **Figs. 9A and 9B** illustrate the principles of intra-cavity coherent addition of several beam distributions derived from separate fiber lasers using discrete beam splitters couplers.

Fig. 9A exemplifies intra-cavity sequential addition configuration. A resonance cavity **700A** is shown including back mirrors **12A-12E**; gain media **16A-16E** (e.g., double-clad fibers); a beam coupler assembly including simple beam splitter couplers **120A-120D**; and an output coupler **14**. The couplers **120A-120E** have 50%, 33.3%m 25% and 20% reflectivities, respectively. Collimation lenses L_1- L_5 are provided in each of the channels, respectively.

Thus, each of the couplers **120A-120D** is a beam splitter of predetermined transmission/reflection. As shown for example for beam splitter **120A**, beams B_1 and B_2 impinge onto the beam splitter **120A**, resulting in an output beam C_1 (and possibly also a losses energy part). If input beams B_1 and B_2 have equal intensities and undergo the 50% beam splitting by the coupler **120A**, then (1) for the two beams being in phase they coherently add at the beam splitter **120A** and no losses occur, (2) at a π phase difference between the beams they interfere destructively at

the beam splitter and there are 100% losses, and (3) at random relative phase between input beams B_1 and B_2 (incoherent) each beam will suffer 50% loss at the beam splitter **120**. If the input beams B_1 and B_2 do not have equal intensities, a suitable transmission should be chosen for the beam splitting region of the coupler **120A** in order to achieve perfect coherent addition when the beams are in phase. Thus, the beams B_1-B_5 are sequentially coherently added during their propagation towards the output coupler **14**: beams B_1 and B_2 are coherently added at the coupler **120A** and a resulting combined beam (C_1) is added to beam B_3 at coupler **120B**, and so on.

Fig. 9B exemplifies intra-cavity coherent addition of pairs in a resonator cavity **700B** including back mirrors **12A-12D**; gain media **16A-16D**; a beam coupler assembly including simple interferometric couplers **120A-120C**; and an output coupler **14**. Coupler **120A** coherently adds channels C_1 and C_2, coupler **120B** adds channels C_3 and C_4, and the resulting combined channels are added at coupler **120C**.

It should be noted, although not specifically shown, that the beam splitters **120A-120C** may be replaced by appropriately designed fiber couplers, for example fiber couplers suitable for coupling light from single-mode fibers [9-11], or those capable of coupling light from multi-mode fibers.

Furthermore, the technique of the present invention provides for imposing the transverse modal content of one beam (one laser channel) on one or more of laser channel beams, and then coherently adding all the beams. This can be achieved with any one of the above-described cavity configurations and coupler designs, provided a suitable aperture is used. In the above-described examples, an aperture was provided in each of the channels, but it is also possible to use only one suitable aperture in one channel and this will automatically impose the same mode distribution on the other channels. The following are some examples of laser cavity configurations utilizing this concept.

Fig. 10 shows a laser cavity **800** including a back mirror **12**; an output coupler **14**; a gain medium **16**; a single-aperture arrangement **818** in one channel associated with laser beam B_1; and a beam coupler assembly including a planar

two-beam interferometric coupler **20**. In the present example, the aperture selects a Gaussian mode from one channel only (that of beam $\mathbf{B_1}$), and at the coupler **20** a Gaussian mode of this channel is imposed on the other channel (beam $\mathbf{B_2}$) and coherent addition of the two beams' distributions is achieved. The operation of this configuration can be understood by considering the losses to various transverse modes in the aperture-less channel (beam $\mathbf{B_2}$). All of the transverse modes, except for the mode present in the other channel $\mathbf{B_1}$, will suffer considerable losses at the intra-cavity coupler **20**, and, if the gain is not too high, these modes will not lase. On the other hand, the common mode for the two channels will suffer no losses and will coherently add. Thus, both the imposing of the modal distribution content and the coherent addition is achieved.

Fig. 11 illustrates the case when a single high-order mode is desired at the output, and thus a single aperture and a single phase element are required in only one of the channels. A resonance cavity **900** is shown differing from that of Fig. 10 in that the single-aperture arrangement **918** and a phase element **905**, configured to create a π-phase step, are located in one channel/beam $\mathbf{B_2}$. Hence, one channel imposes a single high-order transverse mode on the other channel, and coherent addition of the two high order mode distributions is achieved using the single interferometric coupler **20**.

Fig. 12 exemplifies the case when obtaining a specific multimode beam (say with M^2=3) is desired at the output. A resonance cavity **1000** includes a back mirror **12**; an output coupler **14**; a gain medium **16**; a single-aperture arrangement **1018** in optical path of one of four laser beams $\mathbf{B_1}$- $\mathbf{B_4}$ - beam $\mathbf{B_1}$ in the present example; and a planar interferometric beam coupler **220** (as described above with reference to Figs. 3 and 4). The latter is appropriately patterned with coating having a highly reflective coating on its rear facet, and 50%, 33.3, and 25% beam splitting coating on its front facet. Here, a single suitable aperture is provided in one of the channels, and thus one channel imposes a specific multimode content on the other channels, and a single interferometric coupler provides sequential coherent addition of the four beams.

Fig. 13 shows a resonance cavity **2000** including a back mirror **12**, an output coupler **14**, a gain medium **16**, a beam coupler assembly including a planar two-beam interferometric coupler **20**; and a single-aperture **2018** located in the common (combined) channel **C**. Using only a single aperture in the common channel, where the two or more channels coincide, introduces losses to the common multimode beam at the output of the coupler **20**, so that only the desired Gaussian or multimode beam (depending on the aperture diameter) will lase. If single high-order mode operation is desired, then also a single phase element or other mode selecting element in one of the channels is needed, in which case only a specific single high-order mode beam will lase.

It should be noted that all the above-described configurations provide for achieving intra-cavity phase locking of laser beams, because in order to coherently add beams they must be phase locked. With all the above configurations it is possible to use a highly reflective mirror as the output coupler **14** and change the back mirrors **12** by output couplers, and thus obtain several phase locked beams at the output. The above-described configurations involve strong coupling between the channels, which might be undesired with low gain lasers.

The present invention provides for intra-cavity phase locking of laser beams with "weak" couplers. Referring to **Fig. 14**, there is illustrated a resonator cavity **3000** configured for intra-cavity phase locking of two laser beams with a phase locking beam coupler assembly. The device **3000** includes a back mirror **12**, an output coupler **14**, a gain **16**, a double-aperture arrangement **18**, and a phase locking interferometric coupler **420**. This coupler is related to the above-described couplers, but is used to perform only the phase locking and not the coherent addition of the beams into one beam. The coupler **420** is generally similar to the coupler of Fig. 1 (planar interferometric two-beam coupler), but distinguishes therefrom in that a high reflection coating **(21B'** in Fig. 1) and a 50% beam splitter coating **(21A'** in Fig. 1) are both replaced by partially transmitting coatings **25**. The coating **25** may, for example, be of 80% transmission. In case of different intensities of input beams **A** and **B**, different appropriate transmission values should be chosen for the two coatings. If the two input beams are not phase coupled (random relative phase),

then each beam will suffer about 30% loss at the coupler **420** in a double pass, namely, traveling once through the coupler and then back again through the coupler. But if the input beams are phase coupled, such that the two beams add up coherently on the coupler (forward and back), then the losses for both beams at the coupler are negligible.

Thus, in the configuration of **Fig. 14**, the two beams are transmitted through the coupler **420**. If they are in phase, then in one direction the first channel will pass off power to the second channel (coherent addition at the second beam splitter), while in the reverse direction the second channel will pass off power back to the first channel (coherent addition on the first beam splitter). So, the coupler is sort of a directional tap, enabling exchange of power between the channels. Considering the interferometric coupler **420** and the output coupler **14** with R=1 as one feedback mechanism back into the laser, then the feedback versus the transmission of the beam splitters on the interferometric coupler is as illustrated in **Fig. 15**, showing the calculation results for the feedback after a double pass through the coupler **420**, assuming a 100% reflectivity mirror placed at the output of the coupler. Three graphs $\mathbf{G_1}$-$\mathbf{G_3}$ are shown, corresponding to, respectively, incoherent summation of the beams, and positive and negative coherent summation of the beams. It is thus evident that, with the correctly chosen conditions, even a small coupling percentage (i.e., low reflection percentage) is sufficient to produce big discrimination between the positive coherent summation and the incoherent summation. It should be noted that choosing slightly different transmissions for the beam splitters could further reduce the losses for the positive coherent summation case.

It can be seen that when the beams are in phase, even with strong couplers (transmission<80%) the feedback is high and the losses at the coupler are insignificant. On the other hand, if the beams are not phase locked and have a random relative phase, then the feedback is much lower, and the losses at the coupler are severe (even with T=95%). In this configuration and with more than a few percentage of coupling the laser will "chose" to operate so that the beams will be phase locked. This will occur only if there is at least one common frequency (longitudinal mode) to both laser channels (it might be necessary to insert additional

passive/active optical elements, such as delay plates that can be actively tilted, into the channels to introduce appropriate phase/path delays).

Fig. 16 schematically illustrates how weak coupling can be created between more than two channels by using a sequential coupler generally similar to that of Fig. 14, but with different coatings. A resonance cavity **4000** is shown including a back mirror **12**, an output coupler **14**, a gain medium **16**, a multi-aperture arrangement **318**, and a sequential interferometric coupler **520**. The coupler **520** is a plane parallel plate **21** with different partially transmitting coatings on its front and rear facets. More specifically, the front facet has an anti-reflecting region **21A** and *(N-1)* different partially transmitting(beam splitting) regions, generally at $\mathbf{25^{(i)}}$, 3 such regions being shown in the present example considering 4 light channels (N=4), of, respectively T_1, T_2 and T_3 transmissions. The rear facet has an anti-reflective region 21B aligned with region 21A of the front facet along the cavity axis, and *(N-1)* different beam splitting region (N=4 in the present example) of, respectively T_4, T_5 and T_6 transmissions. All the beams $\mathbf{B_1}$-$\mathbf{B_4}$ are transmitted through the coupler **520**, each giving away or receiving some coupling power to the other channels. The necessary transmissions so as to maximize the feedback (homogeneously among the channels) and minimize the losses at the coupler can be calculated for the case when all beams are in phase and coherently add at the coupler **220**. Here, at least one mutual longitudinal mode for all possible channels should exist so that coherent addition can take place (additional passive/active optical elements, such as delay plates that can be actively tilted, that introduce appropriate phase/path delays could be used). Under these conditions, the laser will automatically operate such that all beams are phase locked. It should be noted that it is possible to interchange the back mirror and the output coupler so that the output phase locked beams are to the left.

Another problem solved by the present invention is associated with the fact that in a large aperture multimode laser resonator, the output power is high (large mode volume), but the beam quality is relatively poor (high M^2). The present invention provides for improving the beam quality of multimode laser resonators by modifying the resonator such that instead of using one highly multimode beam

distribution in the gain medium, an array of Gaussian beam distributions is used, which beams are phase-locked and coherently added within the resonator, to obtain a single Gaussian output beam. As a result, the output power will be lower than with the standard multimode configuration due to the fill factor of the Gaussian distributions, but the beam quality will improve significantly. This conversion from a multimode beam distribution to a Gaussian distribution is done with relatively high efficiency.

Reference is made to **Figs. 17A and 17B** illustrating how an array of four Gaussian beam distributions replaces a corresponding multimode beam distribution. **Fig. 17A** shows schematically a standard multimode resonator including a back mirror **12**, an output coupler **14**, and a gain medium **16** (laser rod) therebetween. **Fig. 17B** shows a resonator configuration **5000** of the present invention including a back mirror **12**, an output coupler **14**, a gain medium **16** of the multimode resonator, a specially designed multiple-aperture arrangement **5018**, and a beam coupler assembly including two interferometric couplers **20A** and **20B**. The multiple-aperture arrangement **5018** consists of four apertures, each with a diameter suitable for Gaussian mode operation. One coupler **20A** is designed and oriented so that it combines one pair of Gaussian distributions **A** and **B** that are horizontally displaced with another pair of Gaussian distributions **A'** and **B'** that are horizontally displaced, resulting in two Gaussian distributions $\mathbf{C_1}$ and $\mathbf{C_2}$ (instead of four) that are horizontally displaced. The other coupler **20B** is oriented so that it combines these two Gaussian distributions $\mathbf{C_1}$ and $\mathbf{C_2}$ into one Gaussian distribution **C**. As indicated above, the laser will tend to operate in the minimal loss state, where all the beams phase lock and add up coherently, provided that there is at least one common longitudinal mode (frequency) for all four channels. This could be achieved by inserting additional optical elements into the channels to obtain the appropriate optical path lengths.

It should be understood that a similar configuration but for 16 Gaussian distributions will require four interferometric couplers, and special care must be taken to fulfill the common longitudinal mode requirement. Generally speaking, if the common frequency requirement is fulfilled, this scheme can be extended even

further. It should also be noted that the example of Fig. 17B, using an array of Gaussian beams and intra-cavity interferometric couplers, could be extended to other configurations where an array of low order multimode beam distributions and other types of couplers (as described above) are used.

A possible Nd:YAG laser experimental setup is shown in **Fig. 18** and generally designated **6000**. The resonator is basically about 70cm long plano-concave resonator, with a concave (R = 3 m) output coupler **14** of 40% reflectivity at 1064nm and a high-reflective flat mirror **12**. An (A) Nd:YAG rod **16** of 5mm diameter and 10cm length, with 1.1% doping, is placed in a diffusive ceramic pump chamber. The resonator includes a double aperture **18** with two apertures of 1.6 mm diameter each, positioned 2.4mm apart (between centers), and a high quality thin film polarizer **30**. In general a polarizer is not needed, however in order to obtain high accuracy in the coatings transmission and to exploit Brewster angle instead of AR coating, a single polarization state is preferable. The 3mm thick interferometric coupler **20** is positioned at Brewster's angle. Half of its first (front) facet is coated with a 50% beam splitter coating **21A'**, and half of its second (rear) facet is coated with a high reflective coating **21B'** (no AR coatings). An optional arrangement **32** comprised of an electro-optical LiNbO3 crystal and a $\lambda/4$ retardation plate can be used for Q-switching. CCD cameras (near filed camera and far field camera) **34A** and **34B** and Spiricon Laser Beam Analyzers are used for detecting and characterizing the near and far field intensity distributions.

Thus, the present invention provides novel resonator cavity configurations, as well as couplers to be used therein, for achieving intra-cavity phase locking or phase locking and coherent addition of two or more Gaussian beams, two or more single-high-order-transverse-mode beams, and two or more transverse multimode beams. The technique of present invention provides for imposing the modal distribution content of one channel on all other channels within the laser resonator cavity, and coherently combining all these distributions to obtain a single powerful beam at the output, with the desired modal content.

The technique of the present invention provides for designing compact, stable and practical laser systems whose outputs will have both high power and

high beam quality, much above those from single channel high power lasers. The compactness of the single-substrate coupler enables the combined lasers to "share" optical components such as the end resonator mirrors. This further improves the stability of the combined system, as vibrational and thermal noises are largely common-mode-rejected. The flexibility to design and fabricate complex elements on a single substrate enables control of the coupling strength so as to optimize the trade off between coupling and loss (for high-gain lasers strong coupling between the lasers in required for phase locking, whereas for low-gain lasers weak coupling is better). In the technique of the present invention, external polarization manipulation can be used as an additional degree of control. Indeed, the use of orthogonal polarizations for two lasers will enable efficient addition even without interferometric stability. Slightly different wavelengths may also be used for the same purpose. The couplers can be designed to combine lasers operating with higher order modes, and even multimode beams, enabling even higher total powers than with lasers operating with the single fundamental mode. Single-substrate optical elements can be mass produced, and offer substantial savings in manufacturing, assembling and combining of many individual lasers.

The technique of the present invention can be applied to a wide variety of lasers (gas, solid state, diode, fiber, microdisk, etc), a variety of stable resonators, and various modes of operation (CW, pulsed, etc), which could be used in industrial, medical, and military applications.

Those skilled in the art will readily appreciate that various modifications and changes can be applied to the embodiments of the invention as hereinbefore described without departing from its scope defined in and by the appended claims.

CLAIMS:

1. A resonator cavity comprising at least one gain medium and end reflectors which define together longitudinal modes of light in the cavity, the cavity further comprising

(a) a beam coupler assembly operable to split light impinging thereon into a predetermined number of spatially separated light channels, and to cause at least partial coherent combining of the light channels, having common longitudinal and transverse modes, in a double pass through the beam coupler assembly, to thereby produce at least one output combined light channel;

(b) an aperture arrangement configured to select, in at least one of said spatially separated light channels, a predetermined transverse mode that is desired at the cavity output.

2. The resonator cavity of Claim 1, wherein the beam coupling assembly is configured to provide coherent combining of the light channels to produce the single output combined channel.

3. The resonator cavity of Claim 1, wherein the beam coupling assembly is configured to provide partial coherent combining of the light channels to produce the multiple spatially separated output combined light channels, which are phase locked.

4. The resonator cavity of Claim 2, wherein the beam coupler assembly includes at least one simple beam splitter/combiner.

5. The resonator cavity of Claim 2, comprising N gain media producing N light channels, respectively, said beam coupler assembly including $(N-1)$ simple beam splitter/combiners.

6. The resonator cavity of Claim 1, wherein the beam coupler assembly is configured as an interferometric coupler assembly.

7. The resonator cavity of Claim 6, wherein the interferometric coupler assembly comprises a plane parallel plate, each of front and rear facets of the plate having a predetermined pattern formed by regions of predetermined transmission or reflectivity, the plane parallel plate having a predetermined thickness d and being

oriented with respect to a light propagation axis at a predetermined angle defining a certain angle α of light incidence onto the plate so as to ensure said splitting and said at least partial coherent combining of the light channels in the double pass through the plate.

8. The resonator cavity of Claim 7, wherein for the incident angle α, the thickness *d* of the plate is determined as:

$$d = x_0 / \{2 \cos\alpha \; tg[\arcsin(\sin\alpha / n)]\}$$

wherein x_0 is a distance between propagation axes of the light channels, and *n* is a refractive index of a material of the plate, thereby providing for matching the distance between the light channels so as to enable an optimal overlap between the light channels and their collinear propagation after exiting the beam coupler assembly.

9. The resonator cavity of Claim 7, wherein the front facet includes a substantially light transmitting region, and at least one region of a predetermined beam splitting property; and rear facet includes a relatively large highly reflective region, the dimensions of the regions on the front and rear facets and the orientation of the plane parallel plate being such that: the substantially transmitting region of the front facet is aligned with the highly reflective region of the rear facet thereby allowing light passage through the plate to the highly reflective region where light is reflected towards the beam splitting region in the front surface and reflected back to the highly reflective region on the rear facet.

10. The resonator cavity of Claim 9, wherein the rear facet comprises a substantially transmitting region aligned with the beam splitting region of the front facet.

11. The resonator cavity of Claim 10, wherein the output end reflector is accommodated in an optical path of light emerging from said rear facet.

12. The resonator cavity of Claim 9, wherein the output end reflector is accommodated in an optical path of a light portion that is incident on the front facet and reflected therefrom.

13. The resonator cavity of Claim 10, wherein the output end reflector is accommodated in an optical path of a light portion that is incident on the front facet and reflected therefrom.

14. The resonator cavity of Claim 9, wherein the substantially transmitting region of the facet is formed by an anti-reflecting coating on the facet.

15. The resonator cavity of Claim 10, wherein the substantially transmitting region of the facet is formed by an anti-reflecting coating on the facet.

16. The resonator cavity of Claim 7, wherein the interferometric coupler assembly comprises the single plane parallel plate.

17. The resonator cavity of Claim 7, wherein the front facet of the plane parallel plate comprises the single beam splitting region, thereby producing two light channels.

18. The resonator cavity of Claim 7, wherein the front facet has said substantially transmitting region and *(N-1)* said beam splitting regions for *N* light channels, respectively, each *i*-th beam splitting region, i=2,...N, having a reflectivity of (1-1/i) or transmittance of 1/*i*, such that the first light channel is substantially not affected by the front facet and the other *(N-1)* light channels are differently affected by said *(N-1)* beam splitting regions, respectively.

19. The resonator cavity of Claim 3, wherein the beam coupler assembly is configured as a phase locking interferometric coupler assembly.

20. The resonator cavity of Claim 19, wherein the phase locking interferometric coupler assembly comprises a plane parallel plate, each of front and rear facets of the plate having a predetermined pattern formed by regions of predetermined transmission or reflectivity, the plane parallel plate having a predetermined thickness *d* and being oriented with respect to a light propagation axis at a predetermined angle defining a certain angle α of light incidence onto the plate so as to ensure said splitting and said at least partial coherent combining of the light channels in the double pass through the plate.

21. The resonator cavity of Claim 20, wherein for the incident angle α, the thickness *d* of the plate is determined as:

$$d = x_0 / \{2 \cos\alpha \, tg[\arcsin(\sin\alpha / n)]\}$$

wherein x_0 is a distance between propagation axes of the light channels, and n is a refractive index of a material of the plate, thereby providing for matching the distance between the light channels so as to enable an optimal overlap between the light channels and their parallel propagation after exiting the beam coupler assembly.

22. The resonator cavity of Claim 20, wherein the front facet includes a substantially transmitting region and at least one region of a predetermined partially light transmitting property, and the rear facet includes at least one region of a predetermined partially light transmitting property, the dimensions of the regions on the front and rear facets and the orientation of the plane parallel plate being such that the substantially transmitting region of the front facet is aligned with the partially transmitting region of the rear facet thereby allowing light passage through the plate to the partially transmitting region on the rear facet, where light is reflected from said partially transmitting region of the rear facet towards the partially transmitting region of the front facet.

23. The resonator cavity of Claim 22, wherein the rear facet comprises a substantially transmitting region aligned with the partially transmitting region of the front facet.

24. The resonator cavity of Claim 23, wherein the output end reflector is accommodated in an optical path of light emerging from said rear facet.

25. The resonator cavity of Claim 22, wherein the output end reflector is accommodated in an optical path of a light portion that is incident on the front facet and reflected therefrom.

26. The resonator cavity of Claim 23, wherein the output end reflector is accommodated in an optical path of a light portion that is incident on the front facet and reflected therefrom.

27. The resonator cavity of Claim 22, wherein the substantially transmitting region of the facet is formed by an anti-reflecting coating on the facet.

28. The resonator cavity of Claim 23, wherein the substantially transmitting region of the facet is formed by an anti-reflecting coating on the facet.

29. The resonator cavity of Claim 22, wherein the front facet has said substantially transmitting region and *(N-1)* said partially transmitting regions for *N* light channels, respectively, such that the first light channel is substantially not affected by the front facet and the other *(N-1)* light channels are differently affected by said *(N-1)* partially transmitting regions, respectively.

30. The resonator cavity of Claim 6, wherein the interferometric coupler assembly comprises a pair of first interferometric coupler elements associated with a pair of the gain media, respectively, and operating to produce two combined light components, respectively; and a second interferometric coupler element for coupling said two combined light components, to produce the single output coherently combined channel.

31. The resonator cavity of Claim 30, wherein each of the interferometric coupler elements is a plane parallel plate, each of front and rear facets of the plate having a predetermined pattern formed by regions of predetermined transmission or reflectivities, the plane parallel plate having a predetermined thickness *d* and being oriented with respect to a light propagation axis at a predetermined angle defining a certain angle α of light incidence onto the plate so as to ensure said splitting and said at least partial coherent combining of the light channels in the double pass through the plate.

32. The resonator cavity of Claim 31, wherein for the incident angle α, the thickness *d* of the plate is determined as:

$$d = x_0 / \{2 \cos\alpha \; tg[\arcsin(\sin\alpha / n)]\}$$

wherein x_0 is a distance between propagation axes of the light channels, and *n* is a refractive index of a material of the plate, thereby providing for matching the distance between the light channels so as to enable an optimal overlap between the light channels and their collinear propagation after exiting the beam coupler assembly.

33. The resonator cavity of Claim 30, wherein the front facet includes a substantially transmitting region and at least one region of a predetermined beam splitting property, and the rear facet includes a highly reflective region, the dimensions of said regions and the orientation of the plane parallel plate being such

that the substantially transmitting region of the front facet is aligned with said highly reflective region of the rear facet thereby allowing light passage through the plate to the highly reflective region, where light is reflected from the highly reflective region towards the beam splitting region, reflected back towards the high reflective region, and so on.

34. The resonator cavity of Claim 33, wherein the rear facet comprises a substantially transmitting region aligned with the beam splitting region of the front facet.

35. The resonator cavity of Claim 34, wherein the output end reflector is accommodated in an optical path of light emerging from said rear facet.

36. The resonator cavity of Claim 33, wherein the output end reflector is accommodated in an optical path of a light portion that is incident on the front facet and reflected therefrom.

37. The resonator cavity of Claim 34, wherein the output end reflector is accommodated in an optical path of a light portion that is incident on the front facet and reflected therefrom.

38. The resonator cavity of Claim 33, wherein the substantially transmitting region of the facet is formed by an anti-reflecting coating on the facet.

39. The resonator cavity of Claim 34, wherein the substantially transmitting region of the facet is formed by an anti-reflecting coating on the facet.

40. The resonator cavity of Claim 1, wherein the beam coupler assembly is a polarization coupler assembly.

41. The resonator cavity of Claim 40, wherein the polarization coupler assembly comprises two polarizers accommodated in a spaced-apart relationship along an axis of the cavity; and an optical element configured as a $\lambda/2$ retardation plate or 45° polarization rotator accommodated between the two polarizers.

42. The resonator cavity of Claim 1, wherein said aperture arrangement defines a single aperture associated with one of the light channels.

43. The resonator cavity of Claim 42, wherein said single aperture has a diameter capable of selecting the Gaussian mode distribution, thereby enabling to impose the Gaussian mode of said one light channel on one or more other light

channels and the coherent combining of all the light channels by the beam coupler assembly.

44. The resonator cavity of Claim 42, wherein said single aperture has a diameter capable of selecting the desired multiple-transverse-mode distribution, thereby enabling to impose the desired multiple-transverse-mode distribution of said one light channel on one or more other light channels and the coherent combining of all the light channels by the beam coupler assembly.

45. The resonator cavity of Claim 42, wherein said single aperture has a diameter capable of selecting the single high-order transverse mode distribution, thereby enabling to impose the single high-order transverse-mode distribution of said one light channel on one or more other light channels and the coherent combining of all the light channels by the beam coupler assembly, the cavity further comprising a phase element.

46. The resonator cavity of Claim 43, wherein said one light channel is the output combined light channel.

47. The resonator cavity of Claim 1, wherein said aperture arrangement defines multiple apertures associated with the light channels, respectively.

48. The resonator cavity of Claim 47, wherein each of the apertures has a diameter capable of selecting the Gaussian mode distribution.

49. The resonator cavity of Claim 47, wherein each of the apertures has a diameter capable of selecting the desired multiple-transverse-mode distribution.

50. The resonator cavity of Claim 47, wherein each of the apertures has a diameter capable of selecting the single high-order transverse mode distribution.

51. The resonator cavity of Claim 50, comprising a phase element.

52. The resonator cavity of Claim 47, wherein:

- the multiple apertures are accommodated between the first end reflector and gain medium and include a first pair of apertures accommodated in a spaced-apart relationship along a first axis perpendicular to an axis of the light channel propagation, and a second pair of apertures accommodated in a spaced-apart relationship along said first axis and both spaced from the first pair along a second axis perpendicular to the light channel propagation axis;

- the beam coupler assembly comprises first and second interferometric beam coupler elements accommodated between the gain medium and the second end reflector in a spaced apart relation along the beam propagation axis, the first and second interferometric coupler elements being configured and operable to produce first and second pairs parallel light channels to pass through the first and second pairs of apertures, respectively, coherently combine the first and second pairs of the light channels into two combined light channels, and combine these two light channels into the single output combined channel.

53. A beam coupler element for use in a resonator cavity for controlling light propagating through the resonator cavity to provide an output light channel in the form of coherent addition of at least two light channels having common longitudinal modes, the beam coupler assembly comprising:

a plane parallel plate with its front and rear facets being patterned to have regions of predetermined transmission or reflectivities, wherein

the front facet includes a substantially transmitting region and *(N-1)* beam splitting regions for *N* light channels, respectively, each *i*-th beam splitting region, i=2,...N, having a reflectivity of (1-1/i) or transmittance of 1/*i*, such that the first light channel is substantially not affected by the front facet and the other *(N-1)* light channels are differently affected by the *(N-1)* beam splitting regions, respectively;

the rear facet includes a highly reflective region; and

dimensions of said regions of the front and rear facet and orientation of the plane parallel plate with respect to the light channels' propagation axis are such that light is reflected from the highly reflective region towards the beam splitting region, reflected back from the beam splitting region to the highly reflective region and so on.

54. A beam coupler element for use in a resonator cavity for controlling light propagating through the resonator cavity to provide at least two output light channels of desired transverse and longitudinal modes, the beam coupler assembly comprising:

a plane parallel plate with its front and rear facets being patterned to have regions of predetermined transmission or reflectivities, wherein

the front facet includes a substantially transmitting region and at least one predetermined beam splitting region;

the rear facet includes at least one predetermined beam splitting region; and dimensions of said regions of the front and rear facets and orientation of the plane parallel plate with respect to the light channels' propagation axis are such that light is reflected from the beam splitting region of the rear facet towards the beam splitting region of the front facet and *vice versa.*

55. A method of controlling light propagation in a resonator cavity, which is formed by at least one gain medium and end reflectors that define together longitudinal modes of the cavity, to produce output from the cavity of at least one desired longitudinal and transverse mode distribution, the method comprising:

- splitting light generated by the gain medium into a predetermined number of spatially separated light channels each including light of said at least one desired longitudinal mode;
- selecting in each of the light channels the desired transverse mode content;
- applying interferometric coupling to the light channels so as to cause at least partial coherent combining of the light channels and thereby produce at least one combined light channel of the desired longitudinal and transverse mode distribution.

56. A method of controlling light propagation in a resonator cavity, which is formed by at least one gain medium and end reflectors that define together longitudinal modes of the cavity, to produce output from the cavity of at least one desired longitudinal and transverse mode distribution, the method comprising:

- providing a predetermined number of spatially separated light channels each including light of said at least one desired longitudinal mode;
- selecting in each of the light channels the desired transverse mode distribution;
- applying interferometric coupling to the light channels so as to cause at least partial coherent combining of the light channels and thereby produce at least

one combined light channel of the desired longitudinal and transverse mode content.

57. A method of controlling light propagation in a resonator cavity, which is formed by at least one gain medium and end reflectors that define together longitudinal modes of the cavity, to produce output from the cavity of at least one desired longitudinal and transverse mode distribution, the method comprising:

- providing a predetermined number of spatially separated light channels each including light of said at least one desired longitudinal mode;

- selecting in each of the light channels the desired transverse mode distribution;

- applying polarization coupling to the light channels so as to cause at least partial coherent combining of the light channels and thereby produce at least one combined light channel of the desired longitudinal and transverse mode distribution.

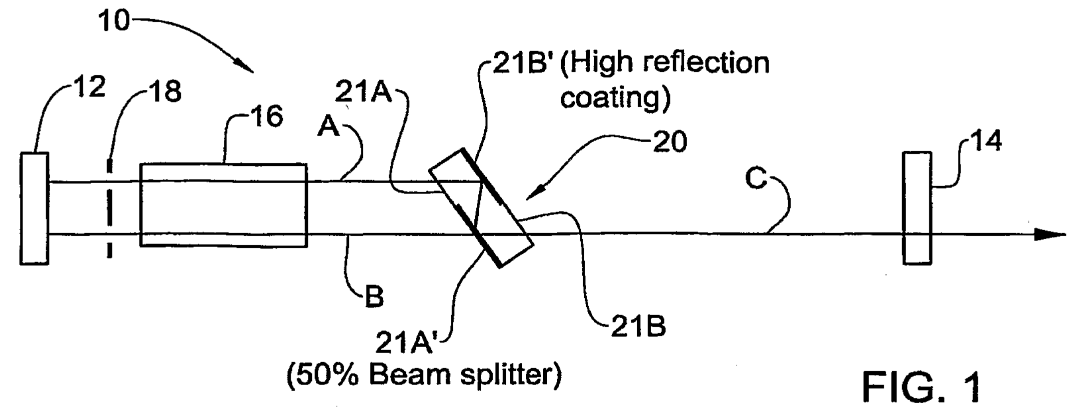


FIG. 1

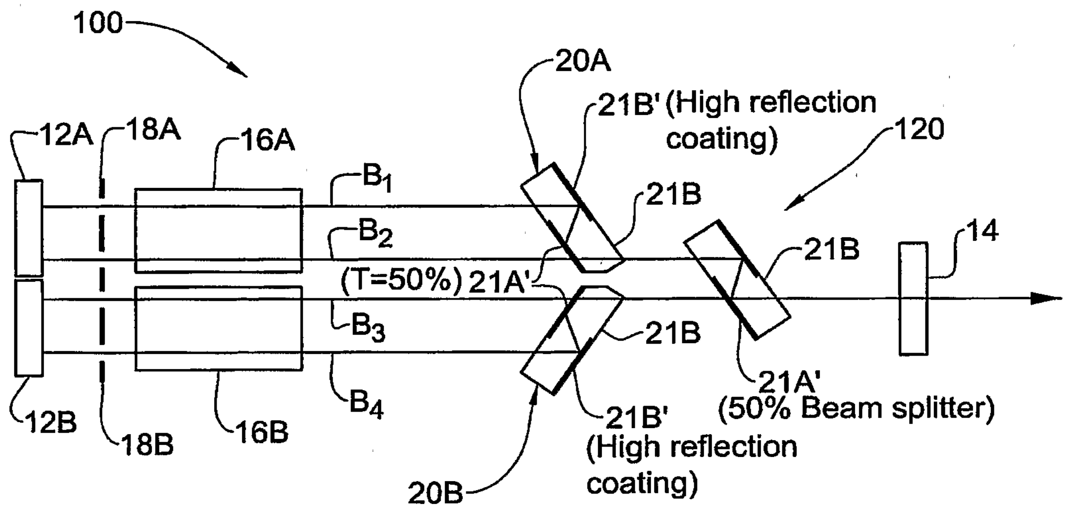


FIG. 2

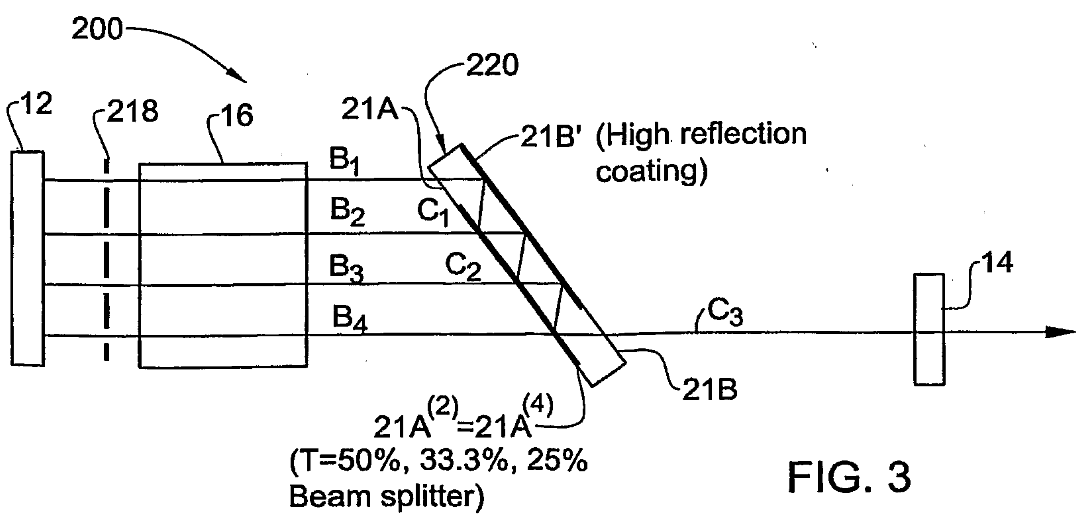


FIG. 3

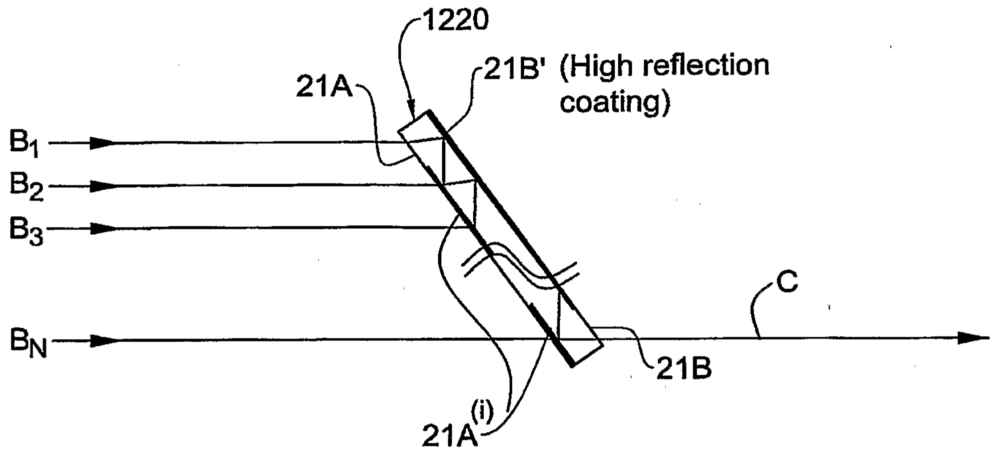

1220
21A
21B' (High reflection coating)
B_1
B_2
B_3
B_N
C
21B
$21A^{(i)}$
(T=0,0.5,0,33,...1/N Beam splitter)

FIG. 4

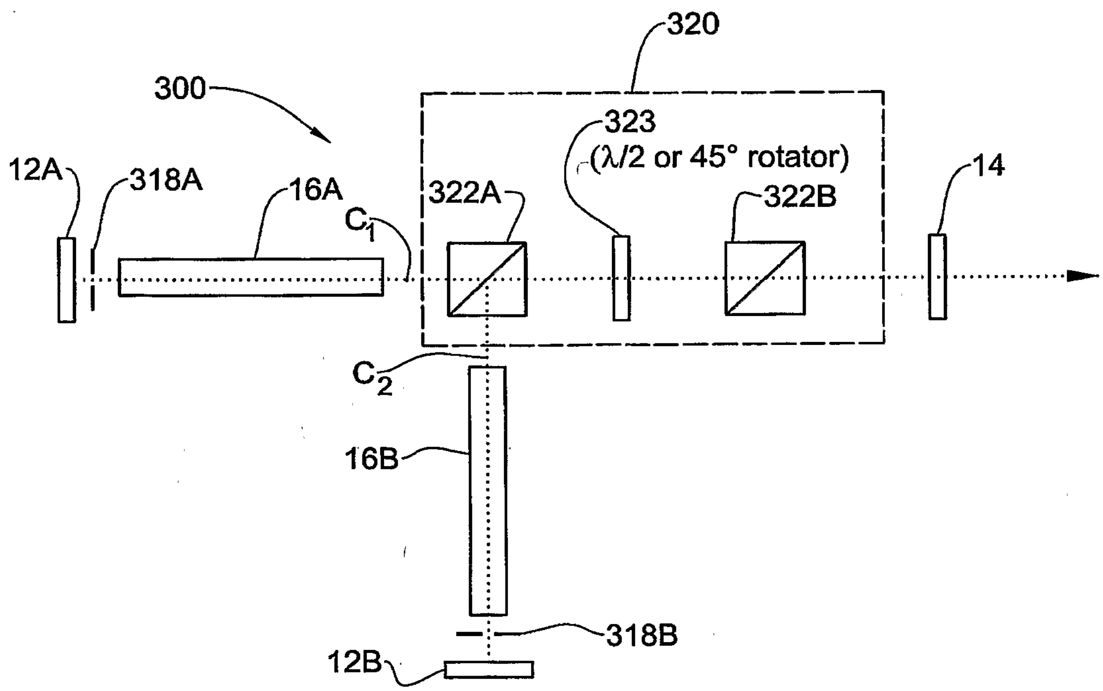

320
300
323
(λ/2 or 45° rotator)
12A
318A
16A
C_1
322A
322B
14
C_2
16B
318B
12B

FIG. 5

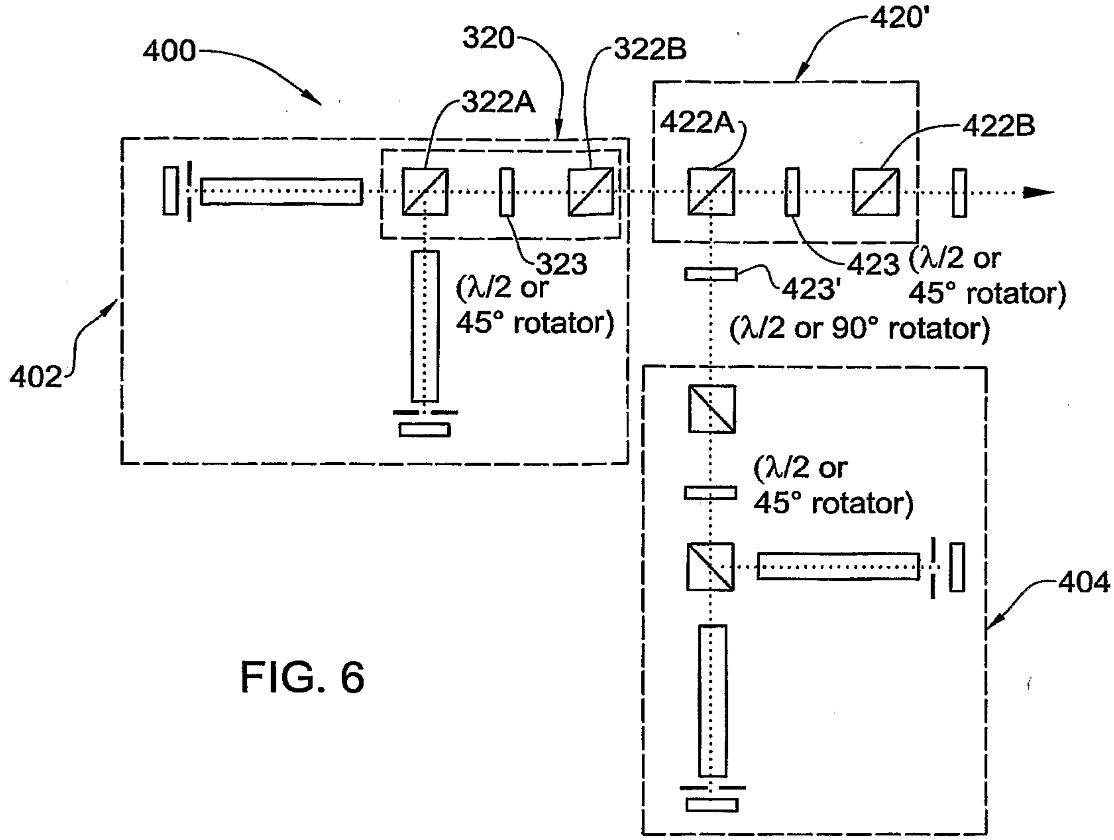

400
320
322B
420'
322A
422A
422B
323
(λ/2 or
45° rotator)
423
(λ/2 or
45° rotator)
423'
(λ/2 or 90° rotator)
402
(λ/2 or
45° rotator)
404

FIG. 6

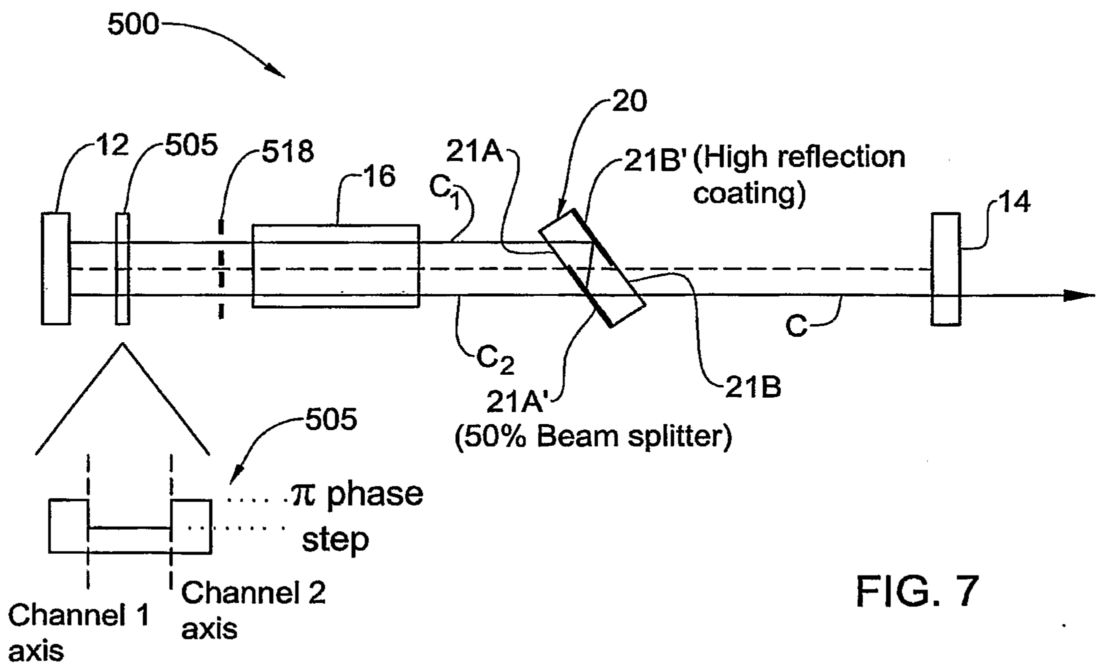

500
20
12
505
518
16
21A
C1
21B' (High reflection
coating)
14
C
C2
21B
21A'
(50% Beam splitter)
505
π phase
step
Channel 1
axis
Channel 2
axis

FIG. 7

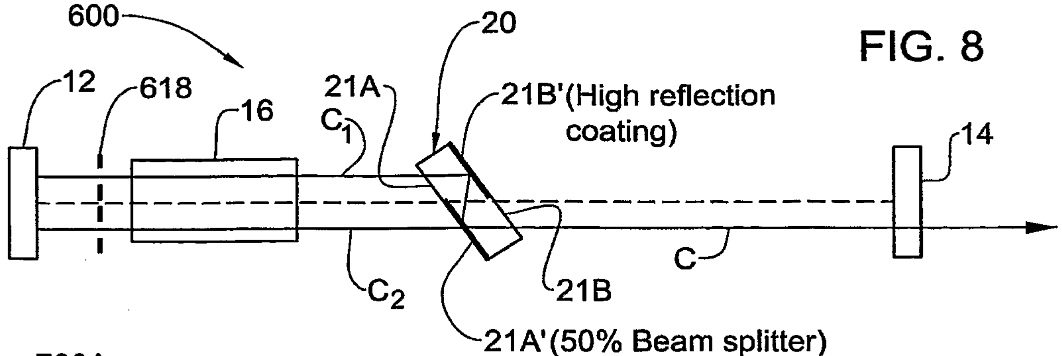


FIG. 8

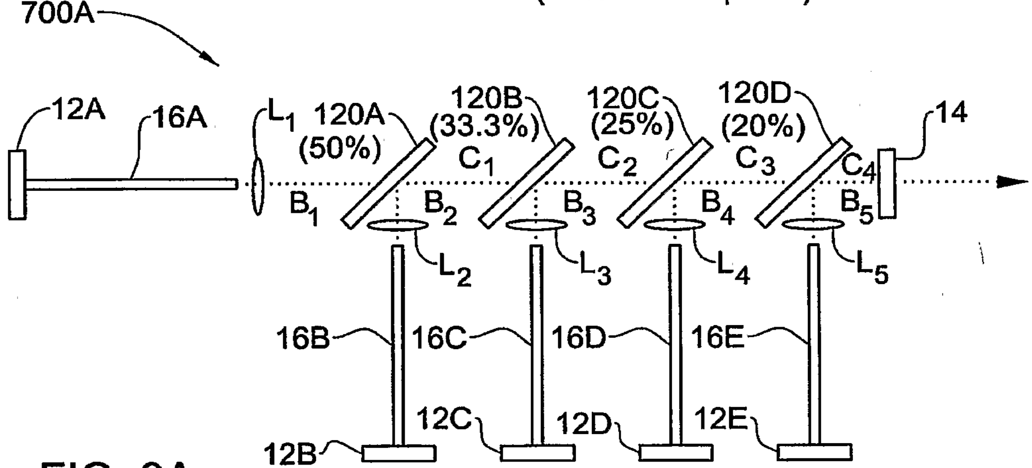


FIG. 9A

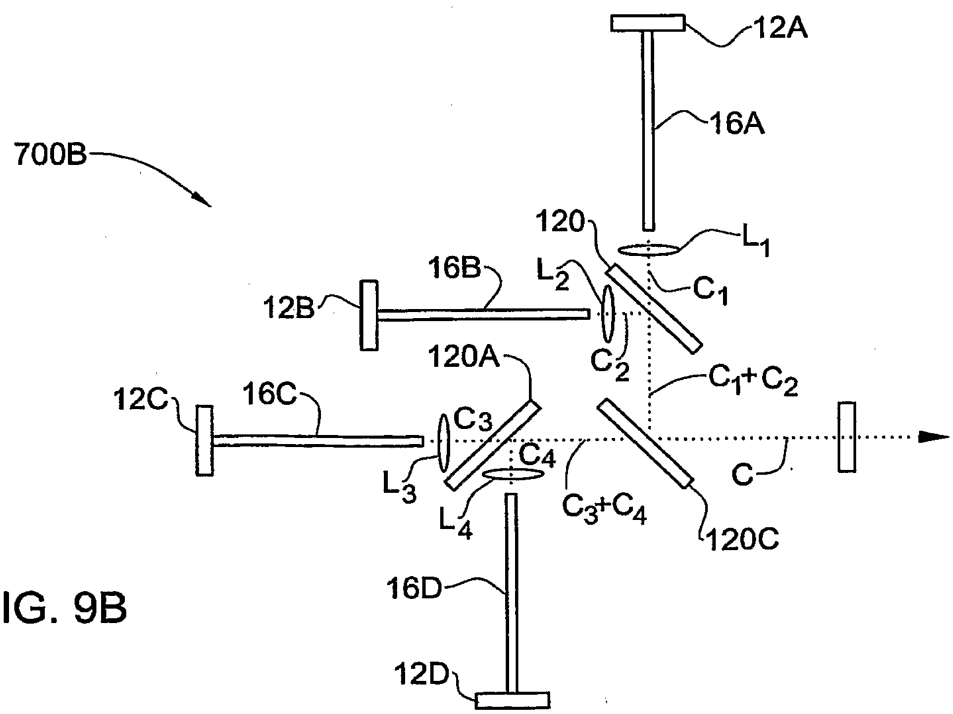


FIG. 9B

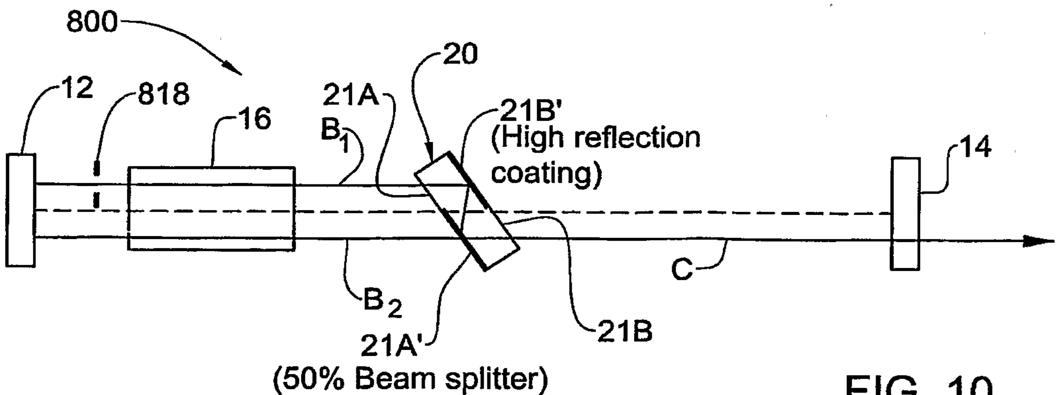


FIG. 10

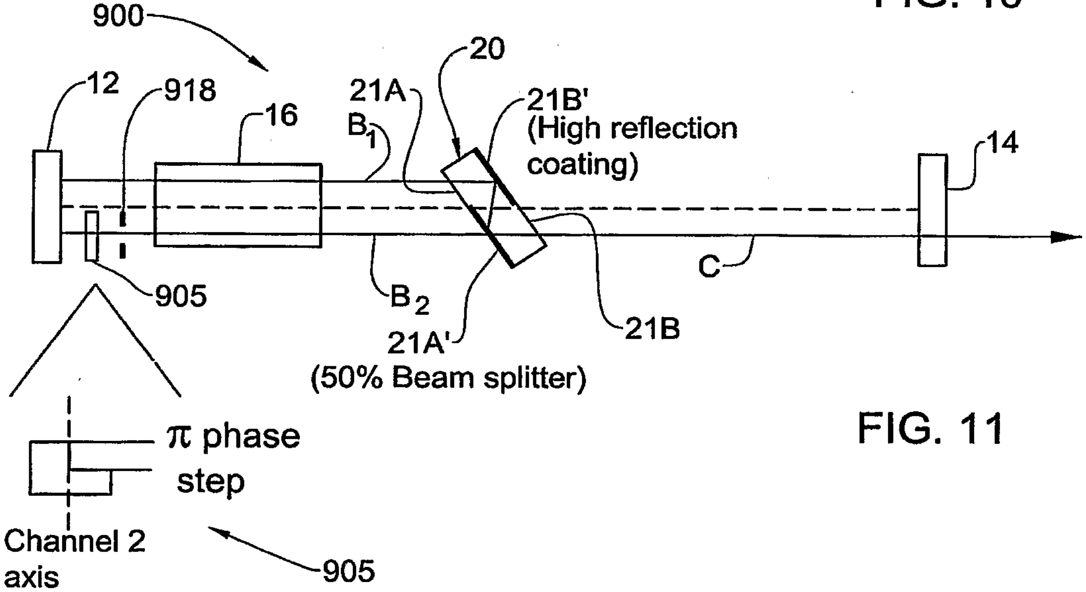


FIG. 11

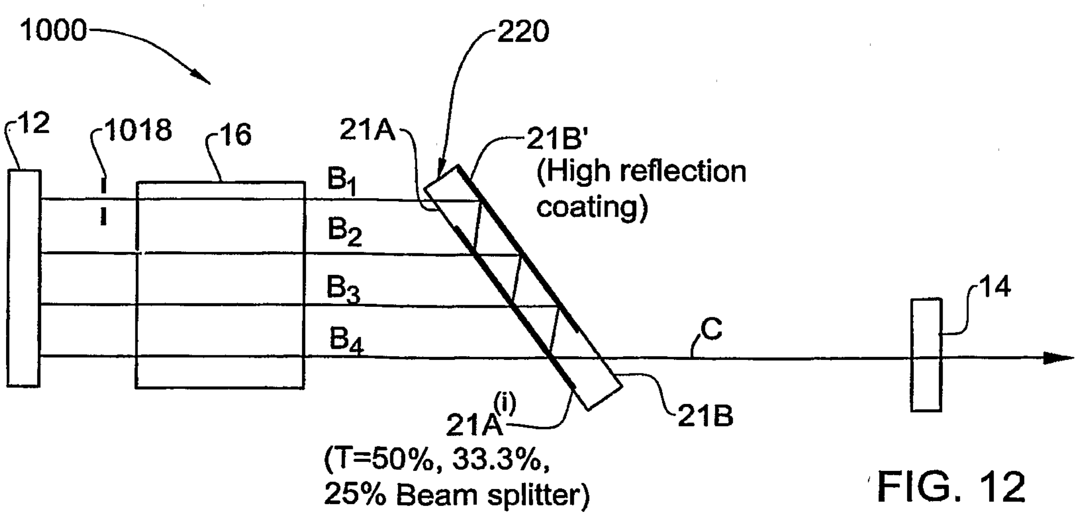
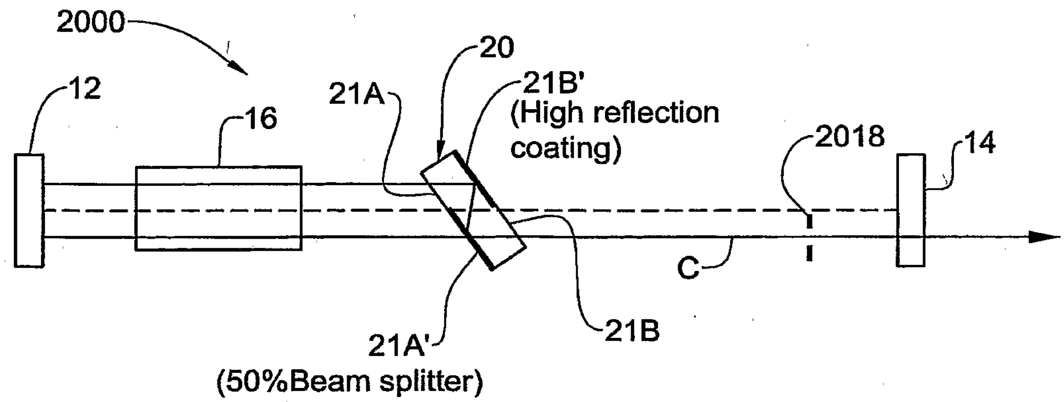
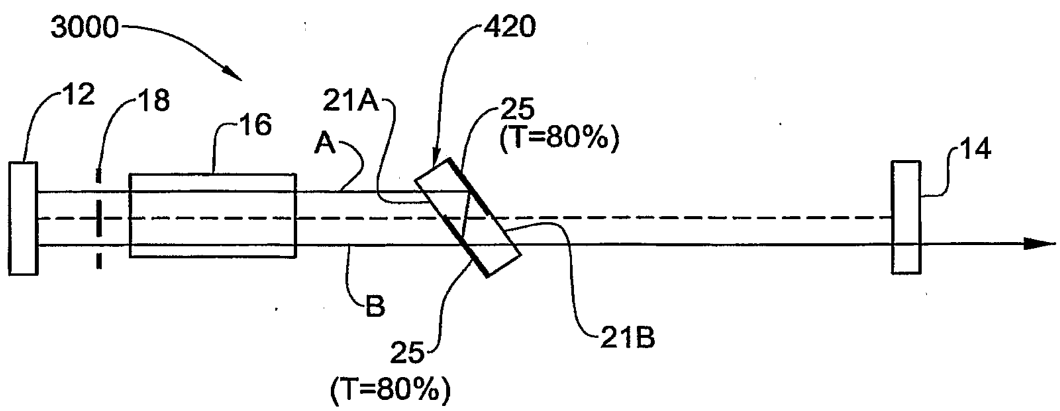


FIG. 12



2000
12
16
21A
20
21B'
(High reflection
coating)
2018
14
C
21A'
(50%Beam splitter)
21B

FIG. 13



3000
12
18
16
A
21A
420
25
(T=80%)
14
B
25
(T=80%)
21B

FIG. 14

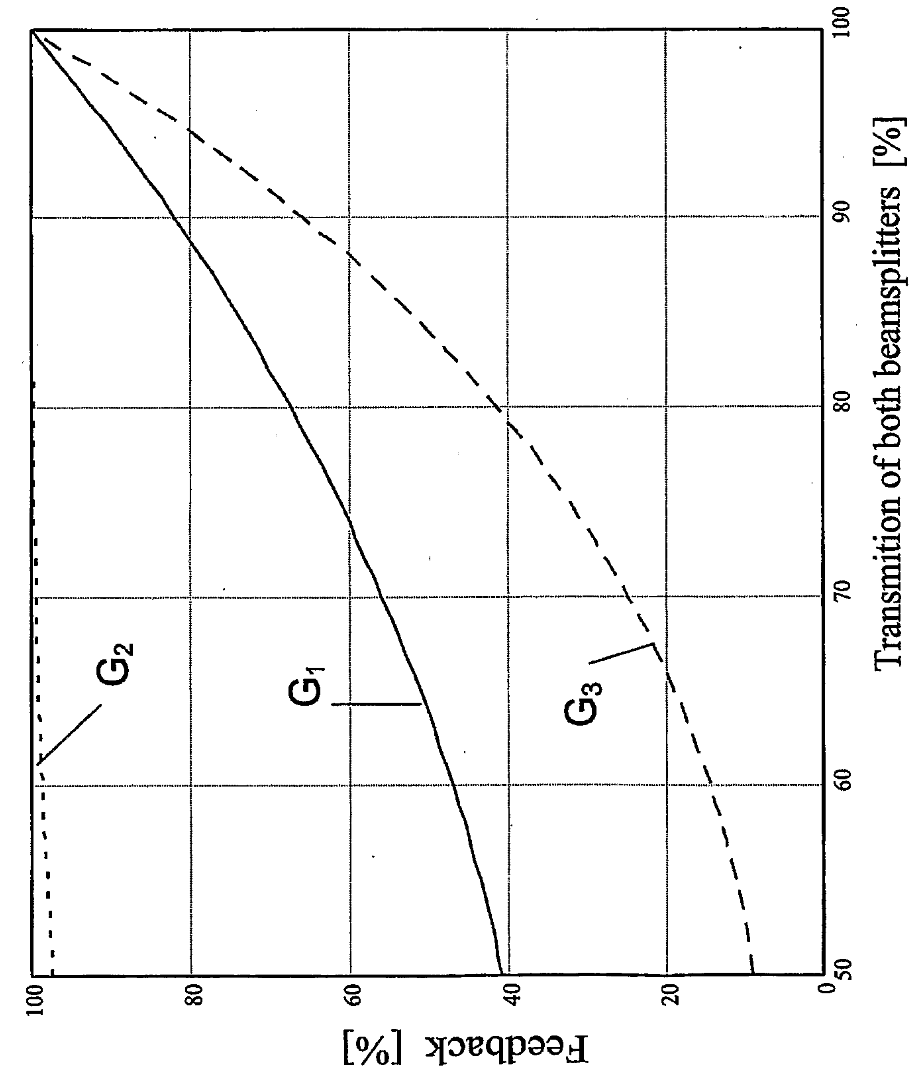

Feedback [%]
Transmition of both beamsplitters [%]
0
20
40
60
80
100
50
60
70
80
90
100
G1
G2
G3

FIG.15

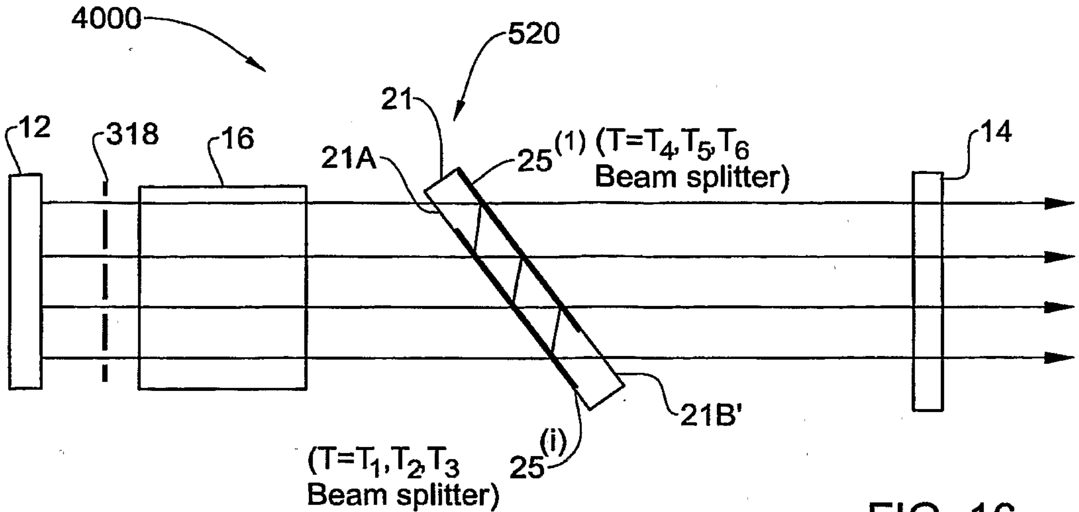


FIG. 16

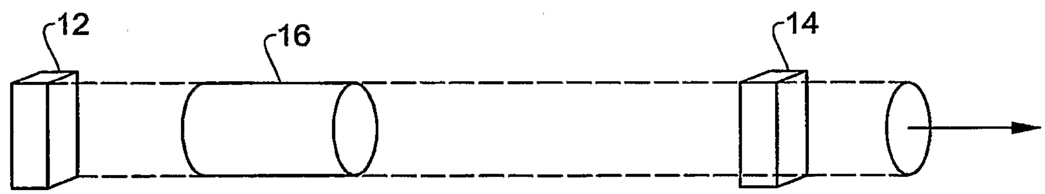


FIG. 17A
(GENERAL ART)

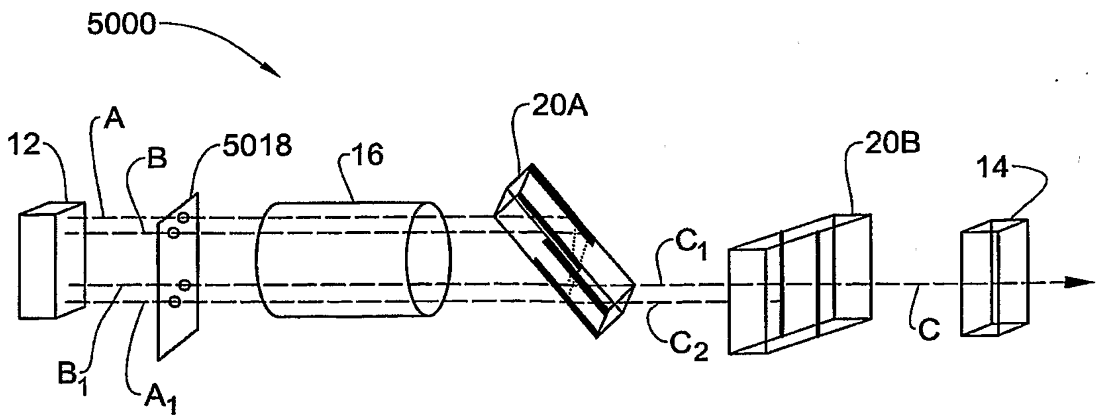


FIG. 17B

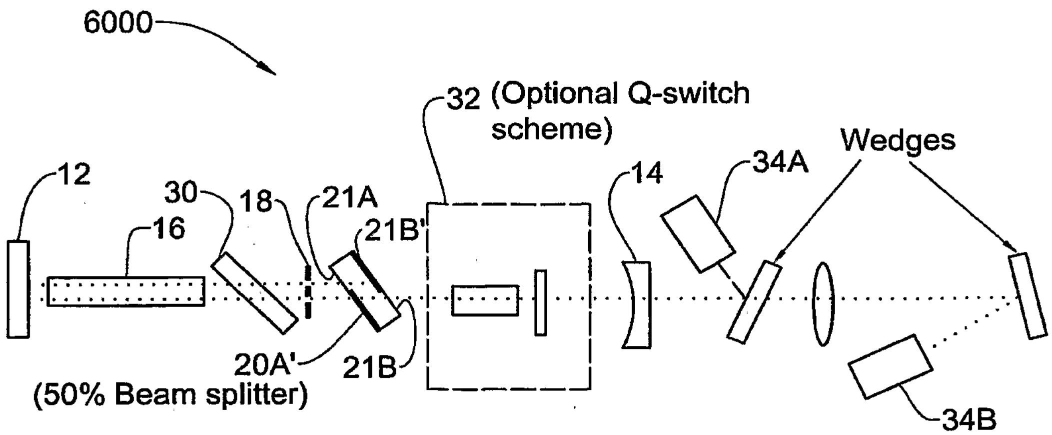

6000
32 (Optional Q-switch scheme)
Wedges
12
30
18
21A
21B'
16
14
34A
20A'
(50% Beam splitter)
21B
34B

FIG. 18